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MANUFACTURING INVOLVING FORGING OF MULTIPLE OBJECTS IN CONTACT

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Summary

Finite element modeling of multi-object manufacturing processes is presented with supporting experiments. The underlying finite element implementation is based on the flow formulation and further coupled with thermal and electrical models to accomplish electro-thermo-mechanical simulation. All three models are implemented with contact algorithms that can take care of the interactions between multiple objects. Focusing on the mechanical aspects, this presentation includes simulations and experiments designed for testing mechanical contact between plastically deforming parts of similar and dissimilar materials. While being plastically deformed against each other under increasing forging load, the parts dynamically develop their mutual contact interfaces. Comparisons of the final geometry as well as force-displacement curves are evaluated. The potential of simulated applications are discussed for the purpose of joining technologies involving plastic deformation and contact.

1. Introduction

A number of joining techniques involves plastic deformation of one or more objects in contact. Different types of joining exist within these techniques covering mechanical joining by geometrical interlocking and metallurgical joining facilitated by high normal pressure and surface expansion and eventual heating. A complete overview is provided in [1], where, among others, the following processes are covered: riveting, including self-pierce riveting, clinching, joining by forming (mechanical joining), cold welding, friction welding, friction stir welding and resistance welding (metallurgical joining).

The present paper focuses on plastic deformation of parts in contact, which are in common for all of the above joining techniques. The plastic deformation is treated by rigid-plastic analysis by the irreducible flow formulation as implemented in the three-dimensional finite element computer programs I-Form3 [2] and SORPAS 3D (by SWANTEC Software and Engineering ApS).

Contact between deformable objects has been recently implemented [3], and some of the experiments for verification of the contact

algorithms are presented here as forging of objects in contact. Geometrical comparison of experiments and simulations by cross-sections serve as verification together with comparison of force-displacement curves.

With verified models combining plastic deformation and contact, the two computer programs can be used for many of the above listed joining processes. IForm3 has been applied to simulation of joining by forming in innovative joining of tubes [4-5] and SORPAS 3D is applied in simulation of resistance welding processes [6-7].

2. Numerical modeling

This section provides an overview of the numerical implementation utilized in simulation of manufacturing processes, see also [6].

2.1 Coupled flow formulation

The core of the finite element model is the irreducible flow formulation that is used for the simulation of mechanical deformation and resulting stress field. The weak form of the governing equation is given by

$$\begin{aligned} \delta \Pi = & \int_V \bar{\sigma} \delta \dot{\epsilon} dV + K \int_V \dot{\epsilon}_{ii} \delta \dot{\epsilon}_{jj} dV \\ & - \int_S F_i \delta u_i dS + \sum_{c=1}^{N_C} P g_n^c \delta g_n^c = 0 \end{aligned} \quad (1)$$

where the two first terms cover the energy rate of the plastic deformation in volume V with incompressibility enforced by penalty in the second term. An arbitrary admissible variation in the velocity field is indicated by δu , $\bar{\sigma}$ is the effective stress and $\dot{\epsilon}$ is the effective strain rate of which the volumetric part is penalized by the large positive constant K . The third term includes surface tractions F applied over part of the surface S .

Finally, the last term is added to account for contact that will be described further in Section 2.3. This term is based on the penalty method with a large positive constant P ensuring that the relative normal velocities g_n^c of all contact pairs N_C are zero if otherwise resulting in penetration.

The mechanical model is further coupled with electrical and thermal models to handle deformation heating and electrical resistance heating. The electrical model includes the solution of Laplace's equation for the electrical potential and the current density based on the gradient of the potential. The thermal model is similar to the electrical model in terms of conduction, and in addition includes the transient term and heat source terms.

Material properties used in all three models are dynamically updated according to temperature changes during the process.

2.2 Finite element discretization

In three-dimensional analysis of the manufacturing processes, hexahedral elements with eight nodes are chosen for the discretization of the domain volume. These elements are of higher quality than the alternative choice involving tetrahedral elements, but with the expense that meshing and remeshing become more complicated. Recent publications by the authors [6,8] deal with meshing and remeshing based on structured meshing and unstructured meshing by the all-hexahedral meshing technique.

2.3 Contact

As stated by the last term in Eqn. (1), the implemented contact algorithm is based on the penalty method. This is one of two traditional methods, where the other method is based on Lagrange multipliers. The Lagrange multiplier

method is exact, but on the expense of additional unknowns. The penalty method avoids additional unknowns, but suffers from a compromise in the selection of the penalty factor P , which for accuracy should be large, but not too large as it will lead to ill-conditioned system matrices and overall risk of locking.

The augmented Lagrangian method that takes advantages from both of the above methods has become popular [9], but it is still more computationally expensive than the implemented penalty method because it involves iterations in order to find the Lagrange multipliers, and these iterations do not always converge fast [10].

When using hexahedral elements in the volume discretization, the contacting surfaces will result in contact pairs of nodes to quadrilaterals. Two methods are implemented for the identification of the outward normal to the quadrilaterals. One method is to divide the quadrilaterals diagonally, leaving a choice between the two diagonals, or to divide the quadrilateral into four triangles by a temporary center node. Details are available in [3,6].

2.4 Equation solving

The irreducible flow formulation leads to a non-linear equation system that is solved by a combination of direct iterations and Newton-Raphson iterations. When deformable objects are in contact, the solution technique is reduced to direct iterations only.

In all cases, including also the electrical and thermal models, the resulting equation systems during the iterations are linearized. They are assembled in skyline format and solved by a direct, parallel skyline solver. Additional details and source code of the equation solver is available in [6].

3. Forging of objects in contact

A number of compression tests of two objects towards each other have been performed in order to verify the contact algorithm [3]. **Fig. 1** shows two geometrical setups. In **Fig. 1a**, the two specimens form a ball-flat contact with ball radius and cylinder end face radius 12mm. The two specimens in **Fig. 1b** form a cross-cylinder with individual radius 5mm. Each specimen is 10mm wide, 50mm long and 13mm high including the rounded side. The specimens in both setups have a machined centering pin that gives a combined slide fit with the tools. For the cross-cylinder test, additional milled grooves in the tools are used to align the specimens perpendicular to each other.

The stress-strain curves of the materials were obtained by compression tests using Rastegaev's cylindrical test specimens [11]. The stress-strain curves are used in the simulations in smoothed tabulated form.

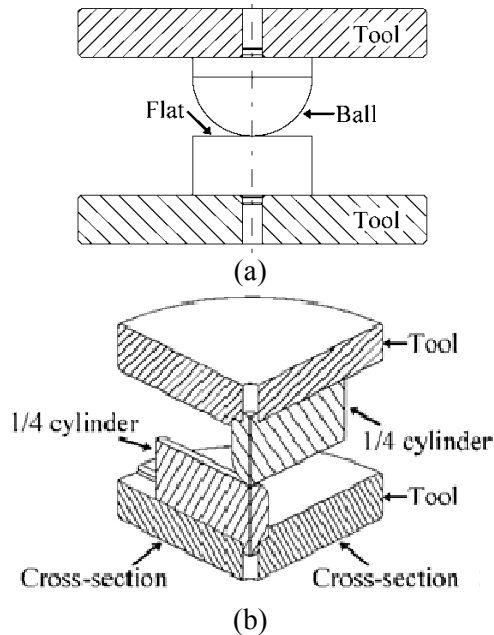


Figure 1. Schematic test setup for (a) ball-flat geometry and (b) cross-cylinder test.

Cross-sectional comparison of experiments and simulations for two reductions of one material combination is shown in **Fig. 2** for the ball-flat geometry. The included example consists of aluminum alloy AA6060-T6 ball geometry forged towards a stainless steel, AISI 316L, cylinder end face. Good agreement between the simulations and the experiments is observed at both levels of reduction, revealing that the combination of plastic deformation and contact is simulated correctly. It is worth noticing the agreement in the shape and size of the contact interfaces.

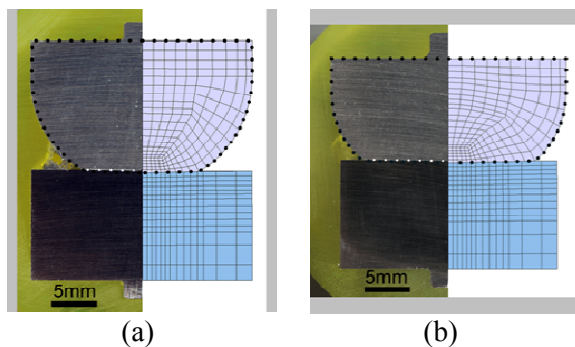


Figure 2. Cross-sectional comparison of ball-flat experiments (left) and simulations (right) at (a) 5.8 % reduction and (b) 17 % reduction.

Fig. 3 includes cross-sectional comparisons for the cross-cylinder test at two levels of reduction when using structural steel S235JR+AR. Good agreement is also found in this case with special focus on the shape and size of the contact interface. Overall geometry is also captured by the simulation as seen at the larger reduction, **Fig. 3b**, where lifting of the specimen ends are observed in both experiment and simulation.

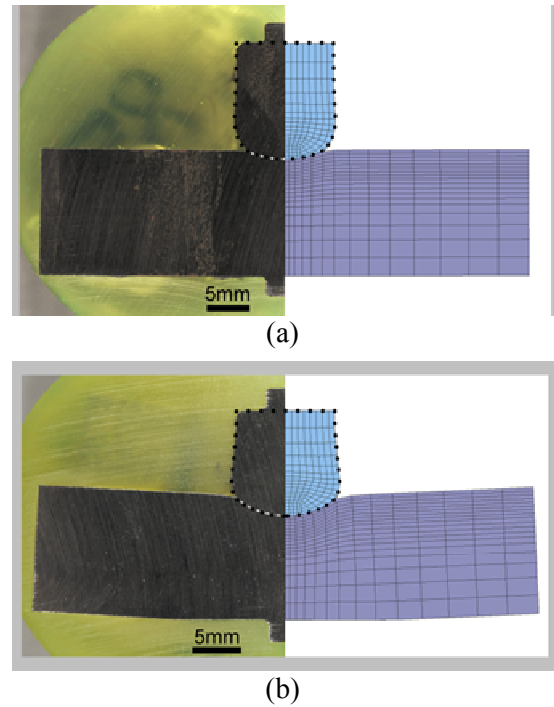


Figure 3. Cross-sectional comparison of cross-cylinder experiments (left) and simulations (right) at (a) 7.9 % reduction and (b) 18 % reduction.

The comparisons in **Fig. 2** and **Fig. 3** are supported by force-displacement curves in **Fig. 4**. The force-displacement curves for the ball-flat geometry are included in **Fig. 4a**, while **Fig. 4b** includes the force-displacement curves for the cross-cylinder test.

Overall agreement is observed between simulations and experiments, though with step-wise changes in the curves stemming from simulations due to discrete contact formation. When new contact pairs are established, the contact area is increased by the area of the new contact pair with a sudden increase of the reaction force as a result. The effect can be minimized by increasing the number of elements, such that the change in contact area develops smoother. The curve corresponding to the crossed-cylinder test shows less tendency of this

effect due to fewer contact pairs developing simultaneously.

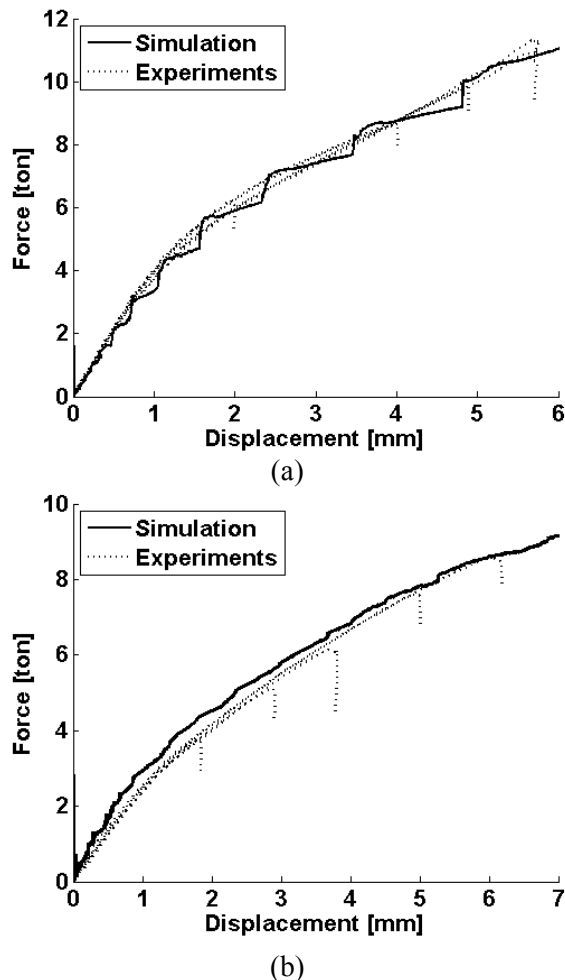


Figure 4. Force-displacement curves for (a) ball-flat compression test and (b) cross-cylinder test. The solid curves correspond to simulations and dotted curves correspond to experiments.

4. Conclusions

A finite element flow formulation with contact is presented and verified by experiments. The experiments are characterized by forging of two objects towards each other with dynamically developing contact as a result.

Selected comparisons of experiments and simulations are presented, covering two geometrical setups and similar as well as dissimilar material combinations. Good agreement is observed for both of the presented cases in terms of geometry by cross-sectional comparison and force-displacement curves.

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